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Regional P-Coda for Stable Estimates of Body Wave Magnitude: Application to Novaya Zemlya and Nevada Test Site Events

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14. ABSTRACT

Regional seismic explosion monitoring requires the discrimination of small clandestine nuclear explosions from background earthquakes. most successful teleseismic discriminant, the so-called *Ms:mb*, discriminant, compares the long-period surface waves magnitude (*Ms*) with th period *P*-based body wave magnitude (*mb*). There are many studies underway to try and extend surface wave magnitude (*Ms)* estimation to re distances and smaller magnitudes. Another problem that is encountered is how to estimate *mb* so that the *Ms:mb* discriminant is meaningful a consistent with teleseismic measures. For small-to-moderate sized events, the teleseismic body wave magnitude, *m*b(*P*), cannot be effectively measured due to low signal-to-noise ratio. We develop a stable regional alternative based on the *P*-coda that scales 1-to-1 with the teleseismic *m*b(*P*), but with the advantage of lower variance. Though *mb*(*Lg*) and *mb*(*Lg*-coda) can be tied to *m*b(*P*) for explosions, they overpredict earth magnitudes by ~0.5-1 magnitude units and degrade the performance of the *Ms*:*mb* discriminant. In contrast, *mb*(*P*-coda) does not exhibit this and can be used to extend *Ms*:*mb* to smaller regional events.

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Table of Contents

1. Executive Summary

This report consists of a manuscript that describe the application of a regional P coda wave methodology to the earthquakes and explosions to Novaya Zemlya and Nevada test site events.

REGIONAL *P*-CODA FOR STABLE ESTIMATES OF BODY WAVE MAGNITUDE: APPLICATION TO NOVAYA ZEMLYA AND NEVADA TEST SITE EVENTS

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Abstract

Regional seismic explosion monitoring requires the discrimination of small clandestine nuclear explosions from background earthquakes. The most successful teleseismic discriminant, the so-called M_s:m_b, discriminant, compares the long-period surface waves magnitude (M_s) with the short-period *P*-based body wave magnitude (m_b). There are many studies underway to try and extend surface wave magnitude (M_s) estimation to regional distances and smaller magnitudes. Another problem that is encountered is how to estimate m_b so that the M_s:m_b discriminant is meaningful and consistent with teleseismic measures. For small-to-moderate sized events, the teleseismic body wave magnitude, $m_b(P)$, cannot be effectively measured due to low signal-to-noise ratio. We develop a stable regional alternative based on the *P*-coda that scales 1-to-1 with the teleseismic $m_b(P)$, but with the advantage of lower variance. Though $m_b(L_g)$ and $m_b(L_g$-coda) can be tied to $m_b(P)$ for explosions, they overpredict earthquake magnitudes by ~0.5-1 magnitude units and degrade the performance of the M_s:m_b discriminant. In contrast, $m_b(P$-coda) does not exhibit this bias, and can be used to extend M_s:m_b to smaller regional events.

Introduction

For sparse local and regional seismic networks, a stable method of determining magnitude is necessary for the development of discriminants, yield estimation, and detection threshold curves. Over the past several years, the U.S. Department of Energy (DOE) laboratories have developed a regional shear-wave coda wave methodology to obtain the lowest variance estimate of the seismic source spectrum [*e.g., Mayeda et al*., 2003; *Phillips et al*., 2003; *Mayeda et al*., 2007]. Unlike traditional magnitudes such as local magnitude (M_L) and teleseismic body wave magnitude (m_b,) which are relative, narrowband measurements that often have regional biases, the coda methodology provides stable, absolute source spectra that are corrected for *S*-to-coda transfer function, scattering, inelastic attenuation, and site effects. The spectra have been used to calculate stable moment estimates (M_w), short-period magnitudes (m_b, M_L), explosion yields, and radiated seismic energy, E_R [*Mayeda and Walter*, 1996; *Mayeda et al.*, 2003; *Murphy et al.*, 2008] from as few as one station. The coda-derived spectra are calibrated for the particular region of interest and are in turn used as input into the Magnitude and Distance Amplitude Correction (MDAC) discrimination procedure outlined by *Walter and Taylor* [2002].

In addition to MDAC's regional high frequency discriminants, the traditional teleseismic discriminant, $M_S{:}m_b$, is currently being extended to smaller events at regional distances. For example, detailed global group velocity measurements are being used to develop models for Rayleigh waves [*Pasyanos et al.*, 2003; *Stevens et al.*, 2001; *Ritzwoller et al.*, 2002; *Levshin et al.*, 2002] that aid in the development of phase-match filters. These models are now being extended to periods as short as 7 seconds. New surface wave magnitude formulas [*Russell*, 2006] and measurement techniques [*Bonner et al.*, 2006] are being developed that allow estimates at these shorter periods that are unbiased with respect to teleseismic M_s estimates. The problem that we are experiencing at the lower magnitudes ($m_b < 4$) is the lack of unbiased body wave magnitudes for discrimination purposes.

We could use L_g and S_n coda-derived m_b estimates; however, this may actually hinder the $M_S{:}m_b$ discrimination performance. Though m_b derived from regional L_g [*e.g., Nuttli*, 1973; *Patton*, 2001] and L_g coda [*e.g., Mayeda*, 1993] have been calibrated for certain regions, both are *S*-based measures, and thus will be biased with respect to earthquakes (Figure 1). For example, the 1992 Little Skull Mountain earthquake at the Nevada Test Site (NTS) had an M_w of 5.5, but would have an $m_b(L_g)$ of ~6.5, whereas the NEIC and ISC m_b's for this event are 5.3. Likewise, if we calibrate $m_b(L_g)$ to teleseismic estimates of m_b for earthquakes, we will underestimate the m_b's for explosions. The use of *S*-based m_b's in the traditional $M_S{:}m_b$ discriminant significantly degrades the discriminant's performance, since it tends to move the explosion and earthquake populations closer together.

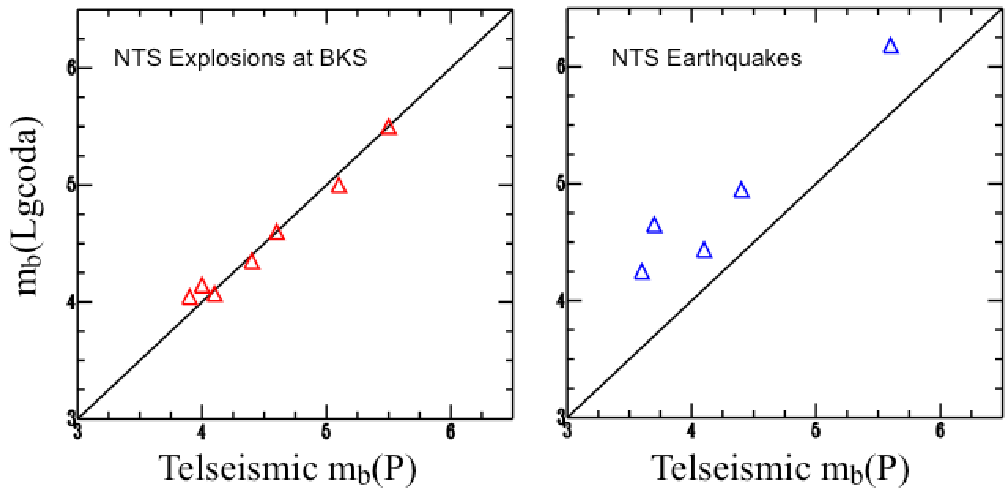

Figure 1. ***m_b*****(*****L_g*****-coda) at station BKS using the method of *Mayeda et al*. [2003] for selected NTS explosions are calibrated against the NEIC teleseismic *m_b* (left) and correlate very well. However, the same path and site corrections applied to NTS earthquakes results in a bias of ~0.5-1 magnitude units (right).**

Regional m_b's have been calculated based on the direct *P*-based phases such as P_n [*e.g.*, *Denny et al*., 1987] and P_g [*e.g.*, *Mayeda*, unpublished manuscript for the Korean Peninsula; *Tibuleac et al*., 2001]. However, *Mayeda* [1993] has shown that these regional measures have significant scatter associated with them, and thus significant numbers of recordings would be required to reduce the variance. The limitation that *Bonner et al*. [2006] faced for small event analysis using their M_s(VMAX) technique was finding an unbiased m_b magnitude. The objective of the current study is to find a more stable estimate of m_b that will use regional and near-teleseismic *P*-wave data.

Characteristics of Novaya Zemlya *P*-coda

The following describes preliminary results using far-regional and teleseismic *P*-coda waveforms from NORSAR, ARCESS, and AWE Blacknest stations. We specifically wanted to determine whether *P*-coda magnitudes would scale with the teleseismic m_b for both earthquakes and explosions. Second, we wanted to ascertain if these *P*-coda magnitudes exhibited less variance than their direct wave counterparts. Figure 2a shows array-averaged P-coda envelopes (2-3-Hz) for three Novaya Zemlya (NZ) explosions (m_b~5.8) recorded at NORSAR, roughly 2200 km epicentral distance. (note: pre-event noise level differences reflect seasonal variations.)

We measured relative *P*-coda envelope amplitudes using the $m_b(P)$ 5.9 August 18, 1983 NZ explosion as a reference event, though any event could have been used (see Table 1 in Appendix 1). By scaling narrowband envelopes between our reference event and the other explosions and earthquakes, we were able to tabulate relative amplitude estimates and hence, m_b estimates. Figure 2b shows *P*-coda-derived m_b estimates (y-axis) relative to the maximum likelihood magnitude m_b(ML) for explosions (red squares) and earthquakes (blue triangles) [*Lilwall and Marshall*, 1986; *Marshall et al.*, 1989; *Bowers*, 2002]. This regression was done using roughly 120 seconds of *P*-coda in the 2-3 Hz band (Figure 2a). These preliminary results are very promising in that earthquake m_b's are also in good agreement with m_b(ML) (Figure 2b).

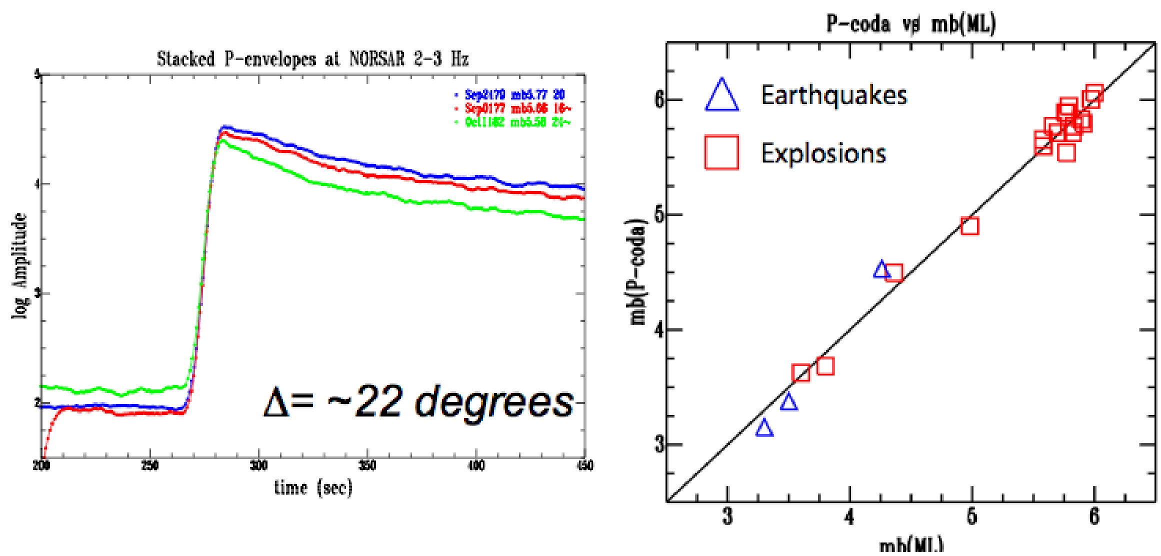

Figure 2. a) Stacked *P*-coda envelopes (2-3 Hz) for selected NZ explosions at NORSAR and ARCESS and amplitudes were made relative to the August 18, 1983 explosion. b) The relative m_b derived from the *P*-coda are shown for both explosions and earthquakes.

Paths from NZ to NORSAR are still at regional distance, and one might expect the *P*-wave and its coda to be comprised of waves that sample the crust and upper mantle over a range of take-off angles from the source. At teleseismic distances however, we might expect that the averaging nature observed for local and regional coda waves to breakdown. At these distances, first arriving *P*-waves are likely emanating from a limited range of take-off angles near the bottom of the focal sphere. To investigate this, we processed roughly 30 NZ explosions recorded at the U.K. arrays, Eskdalmuir in Scotland (EKA) and Yellowknife in Canada (YKA) located at ~30 and 44 degrees from NZ, respectively.

Figure 3 shows *P*-coda envelopes at EKA for 4 NZ explosions with roughly the same magnitude that were located within a few kilometers of each other. We see an immediate discrepancy for the September 24, 1979 event. Though it has the largest m_b(ML) it is roughly a factor of 3 smaller in amplitude (0.5 in $\log_{10}$) at EKA relative to the other three events. The direct *P*-wave, coda, and *PcP* phase (not shown) are all small. In fact, the EKA station magnitude for this event is also low relative to the global m_b(ML) estimate. The closest event is the September 27, 1978 event but this does not appear to be anomalous. Careful inspection of the raw data shows nothing unusual for the September 24th event. (note: the pre-event noise is lower for the October 11, 1982 event because of improvements to the electronics in late 1979). We note that this event at NORSAR is in good agreement with the m_b(ML) as well as at YKA. Assuming this is real, then this suggests a near-source process such as focusing directly beneath this event. Moreover, the scale-length must be small since a nearby event is not affected. This supports the notion that teleseismic *P*-codas will <u>not</u> have the same averaging properties that local and regional codas exhibit.

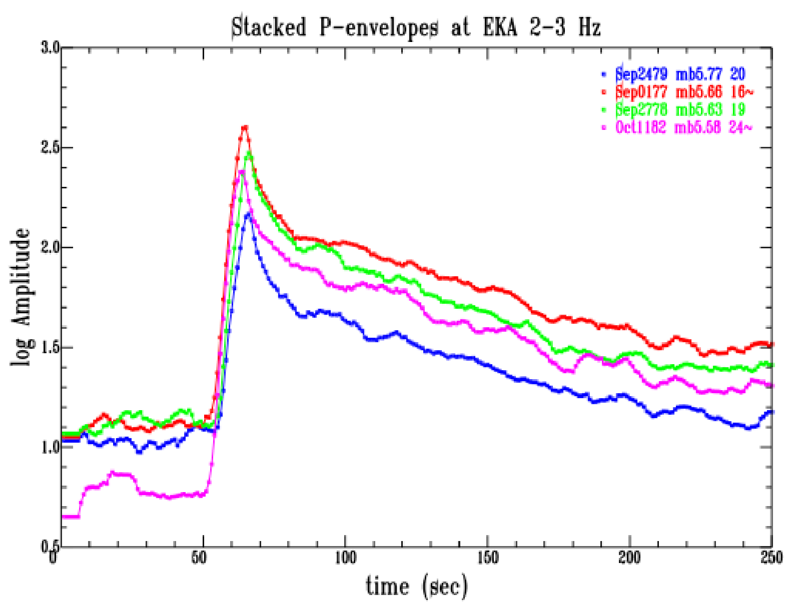

Figure 3. Teleseismic *P*-coda envelopes at EKA for 4 NZ explosions with roughly the same magnitude that were located within a few kilometers of each other. We see an immediate discrepancy for the September 24, 1979 event (blue) suggesting a break-down in the coda's ability to average over the source and path effects.

Our preliminary findings suggest that at regional distances the *P*-coda can be used as a surrogate for teleseismic m_b for both earthquakes and explosions based on the findings at

NORSAR for NZ events (*e.g.*, Figure 2b). At teleseismic distances however, the *P*-coda appears to share the same radiation pattern as the direct *P*-wave and does not appear to average over the focal sphere as is observed for local and regional shear waves. Nonetheless, the derived body wave magnitude m_b(*P*-coda) at EKA and YKA for NZ explosions (not shown) are in good agreement with the globally averaged results using direct teleseismic *P*, though no improvement in scatter is expected.

Characteristics of Nevada Test Site (NTS) *P*-coda

We next focus on near-regional *P*-coda from earthquakes and nuclear tests at the NTS recorded by selected regional broadband stations. Using a single station at roughly 550 km (BKS) we derived m_b(P_g-coda) relations for narrow band envelopes ranging between 1 and 3 Hz. At this distance, we had roughly 60 seconds of *P*-coda before the direct L_g arrival. As with the NZ study, we made relative *P*-coda envelope amplitude measurements for selected earthquakes and explosions which all had independent teleseismic estimates of m_b from the USGS NEIC catalog. Figure 4 shows magnitude results from station BKS operated by the Berkeley Seismological Laboratory. As found with NZ, the near-regional *P*-coda magnitudes do not show a bias, in sharp contrast to m_b(L_g) and m_b(L_g-coda) (*e.g.*, Figure 1).

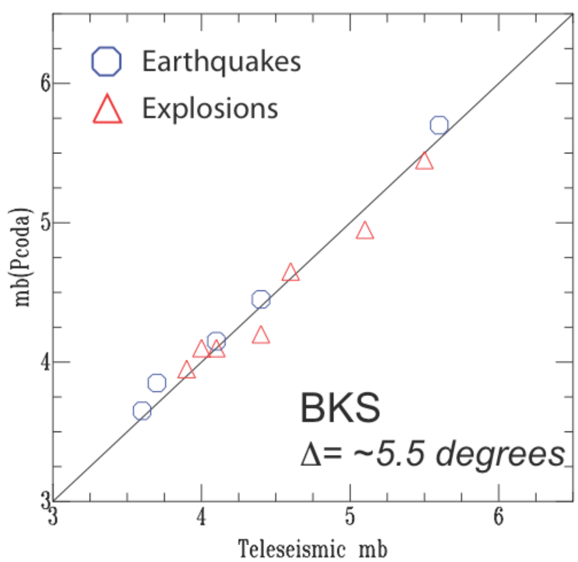

Figure 4. Single station estimates of m_b(*P*-coda) for both NTS earthquakes and explosions plotted against the NEIC teleseismic m_b.

Finally, we compare interstation amplitude measurements to test the extent to which regional *P*-coda can reduce scatter compared to the direct *P*-wave. Figure 5 shows narrowband amplitudes at stations ELK and KNB, roughly 400 and 240 km distance, respectively.

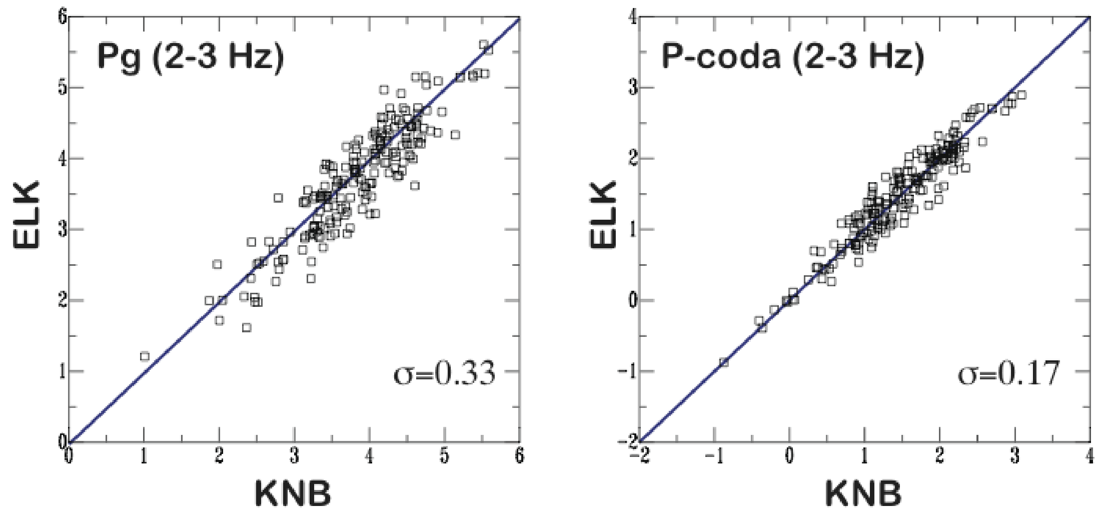

Figure 5. a) Interstation scatter direct P_g is roughly two times larger than *P*-coda for the same NTS events and regional stations, ELK and KNB.

We found that the narrowband regional *P*-coda amplitudes are roughly two times smaller in data standard deviation than their direct wave counterparts. In contrast, for shear wave coda we typically observe a factor of 3-to-4 improvement [*Mayeda et al.*, 2003]. This difference could be due to *P*-coda being more forward scattered and not spatially averaging to the extent of shear-wave codas. This is supported by array analysis from regional waveforms by *Wagner* [1997].

Conclusions

For small-to-moderate sized events, an unbiased, *P*-based regional magnitude is necessary to seamlessly tie to teleseismic estimates of m_b for seismic discrimination and explosion yield studies. Currently there is a debate within the explosion monitoring community as to whether the explosion and earthquake populations in the M_s:m_b discriminant merge or stay separated at smaller magnitudes (< m_b ~3.5). However, due to limited numbers of stations for regional explosion monitoring, direct phase magnitudes such as $m_b(P_n)$ and $m_b(P_g)$ exhibit high variance due to strong lateral complexity and source radiation pattern. Though regional shear wave magnitudes [*e.g.*, $m_b(L_g)$ and $m_b(L_g$-coda)] can be tied to either explosion or earthquake m_b's, the fact that these are shear wave measurements introduces a significant bias [*e.g.*, Figure 1] and will degrade the performance of the M_s:m_b discriminant. We have found a regional equivalent to the teleseismic m_b using *P*-coda envelopes which are roughly two times less scattered than their direct wave counterparts and scales 1-to-1 with teleseismic estimates (*e.g.*, Figure 5b). However, at teleseismic distances, we find evidence that the averaging properties of coda appears to break down perhaps due to sampling only a narrow portion of the bottom of the focal sphere (*e.g.*, Figure 3). Our next step will be to apply the new *P*-coda methodology to other test sites and assess the performance of the M_s:m_b, discriminant for smaller magnitude events. In addition to discrimination, the stable estimation of explosion yield for small tamped events may benefit from the use of the regional *P*-coda envelope and studies are currently underway.

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Appendix 1:

Table 1

```
Explosions:                                                             p1.5    s1.5    p2.0    s2.0
101200  SEP 29 (273), 1976 02:59:57.700 73.36  54.88  5.83  14      0.1     0.2     0.05    0.1
399183  OCT 20 (294), 1976 07:59:58.070 73.398 54.85  4.98  15      -0.62   -0.4    -0.7    -0.45
106976  OCT 09 (282), 1977 10:59:58.120 73.409 54.936 4.36  17*     -1.0    -0.6    -1.05   -0.75
399184  SEP 01 (244), 1977 02:59:57.970 73.327 54.628 5.66  16      0.16    0.2     0.05    0.1
112446  AUG 10 (222), 1978 07:59:57.930 73.298 54.823 6.00  18      0.35    0.22    0.3     0.25
120096  SEP 24 (267), 1979 03:29:58.750 73.343 54.681 5.77  20      0.17    0.22    0.15    0.2
120603  OCT 18 (291), 1979 07:09:58.750 73.316 54.825 5.79  21      0.27    0.21    0.2     0.2
127832  OCT 11 (285), 1980 07:09:57.470 73.305 54.815 5.76  22      0.16    0.16    0.15    0.1
134401  OCT 01 (274), 1981 12:14:57.230 73.304 54.827 5.97  23      0.3     0.28    0.25    0.25
141948  OCT 11 (284), 1982 07:14:58.630 73.339 54.617 5.58  24      -0.1    0.0     -0.1    -0.05
150212  AUG 18 (230), 1983 16:09:58.900 73.358 54.945 5.91  25      0.17    0.17    0.07    0.07
151191  SEP 25 (268), 1983 13:09:58.220 73.32  54.577 5.77  26      -0.07   -0.04   -0.15   0.00
399187  AUG 26 (239), 1984 03:30:00.000 73.326 54.763 3.8   ??    -1.6  -1.4 -1.75 -1.6
(Mikhailov,1999 list of nukes) (Norsar report lowered mb from 4.2 to 3.8)
161897  OCT 25 (299), 1984 06:29:58.120 73.355 54.999 5.82  n25     0.2     0.2     0.00    0.00
196389  AUG 02 (214), 1987 02:00:00.200 73.323 54.607 5.82  n26     0.21    0.21    0.00    0.1
205735  MAY 07 (128), 1988 22:49:58.340 73.315 54.56        5.58    n26     0.0     0.11    -0.05   0.0
213077  DEC 04 (339), 1988 05:19:53.300 73.366 55.01        5.89    n25     0.31    0.25    0.1     0.1
15069   OCT 24 (297), 1990 14:57:58.450 73.317 54.805  ??   n12      NA     NA      NA      NA
399186  NOV 15 (319), 1978 08:30:00.000 73.4   55.0   3.6    ??     -1.72 ??  -1.8    ??
(NORSAR CD, chemical?)

Earthquakes:
185081  AUG 01 (213), 1986 13:56:37.800 73.031 56.726       4.26    ??      -1.0    -0.75   -1.05   -0.75
       (Marshall et al., 1989)
399156  JUN 13 (164), 1995 19:22:37.900 75.2   56.7   3.5   ??      ??      ??      -2.1    ??(Ringdal, 1997)
399161  JAN 13 (013), 1996 17:17:23.000 75.2   56.7   2.4   ??      ??      ??      ??      ??(Ringdal, 1998)

361144  AUG 16 (228), 1997 02:10:59.910 72.648 57.352       3.3     ??      -2.2    ??      -2.25   ??
(Bowers, 2002) 3.5 (Ringdal, 1998)  LLNL envelope screwed up!
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Appendix 2:

Over the past several years, the DOE labs have developed a regional coda wave methodology to obtain the lowest variance estimate of the seismic source spectrum. The coda is the scattered wave train that arrives after the direct arrivals, presumably the result of scattering from heterogeneity in the Earth. Thus, regional M_W and m_b estimates derived from *Sn* and *Lg* coda are very stable, even when only a single station is used. However, these m_b*'s* are inherently biased for earthquakes because they are an *S*-based measurement, and explosions are relatively depleted in *S*-waves. Previous research projects have used region-specific m_b scales based on direct measurements of *Pn* and *Pg* to improve the $M_s{:}m_b$ discrimination, even though the m_b estimates often had a large variance.

Figure 1 shows results for Nevada Test Site (NTS) explosions recorded at regional distances. Here we compare the inter-station performance between m_b(*Lg*), m_b(*Pn*) and m_b(*Lg*coda) from Mayeda (1993). We see that the coda-based m_b's have the lowest standard deviation by roughly a factor of 4-to-5. This property makes it ideal for monitoring situations where station coverage is sparse.

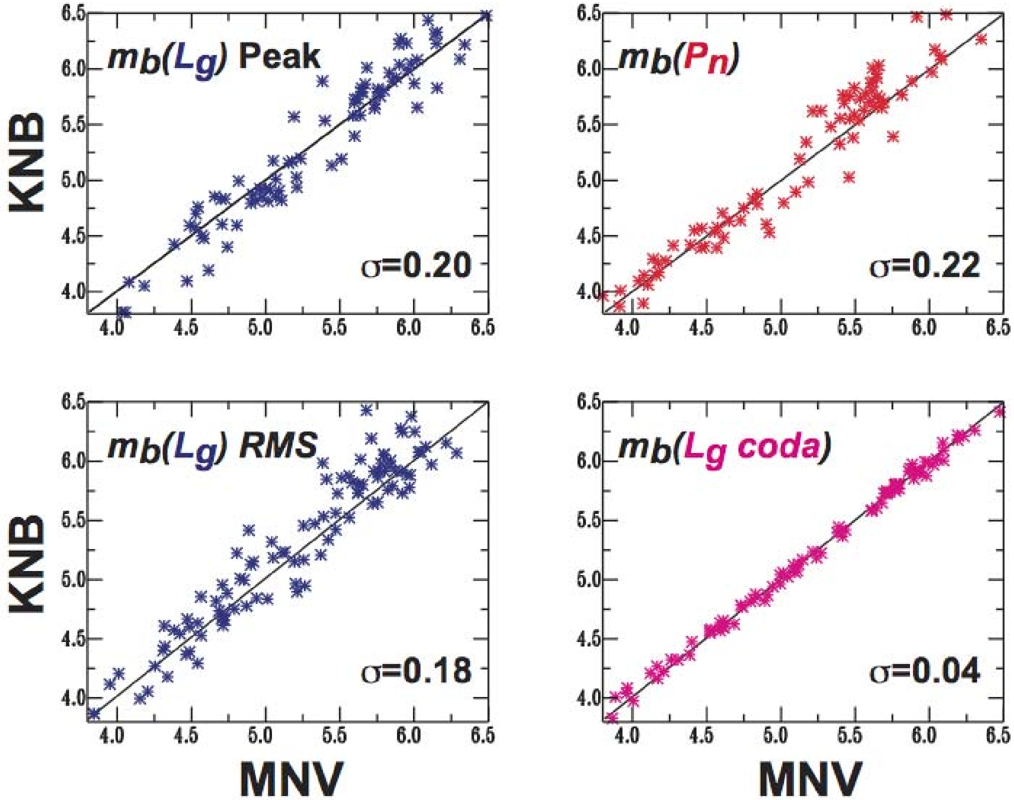

Figure 1. (from Mayeda, 1993)

The next obvious step to be implemented in the coda wave methodology is the use of *P* coda for m_b estimates. The following figures and text describes the results of a two week visit to AWE Blacknest where far-regional and teleseismic *P*-coda were investigated. We specifically wanted to know whether *P*-coda magnitudes would scale with the teleseismic m_b for both earthquakes and explosions. Second, we wanted to know if these *P*-coda magnitudes exhibited less variance than their direct wave counterparts.

Figure 2 below shows array averaged envelopes (2-3-Hz) for two Novaya Zemlya (NZ) explosions (m_b~5.8) recorded at NORSAR, roughly 2200 Km distance. Notice that both *P* and *S* codas are very similar in character. (note: pre-event noise level differences reflect seasonal variations.)

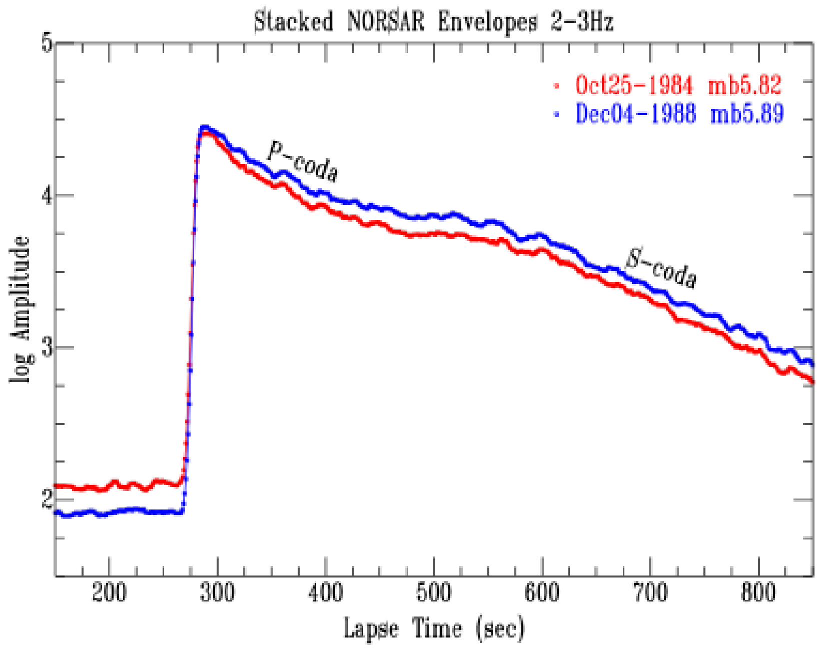

Figure 2.

We measured relative *P*-coda envelope amplitudes using the October, 24, 1990 NZ explosion as a reference event (Table 1). By scaling narrowband envelopes between our reference event and the other explosions and earthquakes, we were able to tabulate relative coda amplitudes. Figure 3 below shows coda envelope amplitude residuals (y-axis) relative to the maximum likelihood magnitude m_b(ML) for explosions (red squares) and earthquakes (blue triangles) (Lilwall and Marshall, 1986; Marshall et al., 1989; Bowers, 2002). This regression was done using roughly 100 seconds of *P*-coda in the 2-3-Hz band. These preliminary results are very promising in that earthquake m_b's are also in good agreement with mb(ML). This is in sharp contrast to results from regional m_b(*Lg*) and m_b(*Lg*coda) (e.g., Patton, 1988; Mayeda 1993). In those studies, m_b was tied to explosions at the Nevada Test Site (NTS) (see Figure 1), however applying the same formulas to earthquakes results in an overestimation of ~1 magnitude unit. For example the 1992 M_W 5.5 Little Skull mountain earthquake at NTS would have an m_b(*Lg*) of ~6.6.

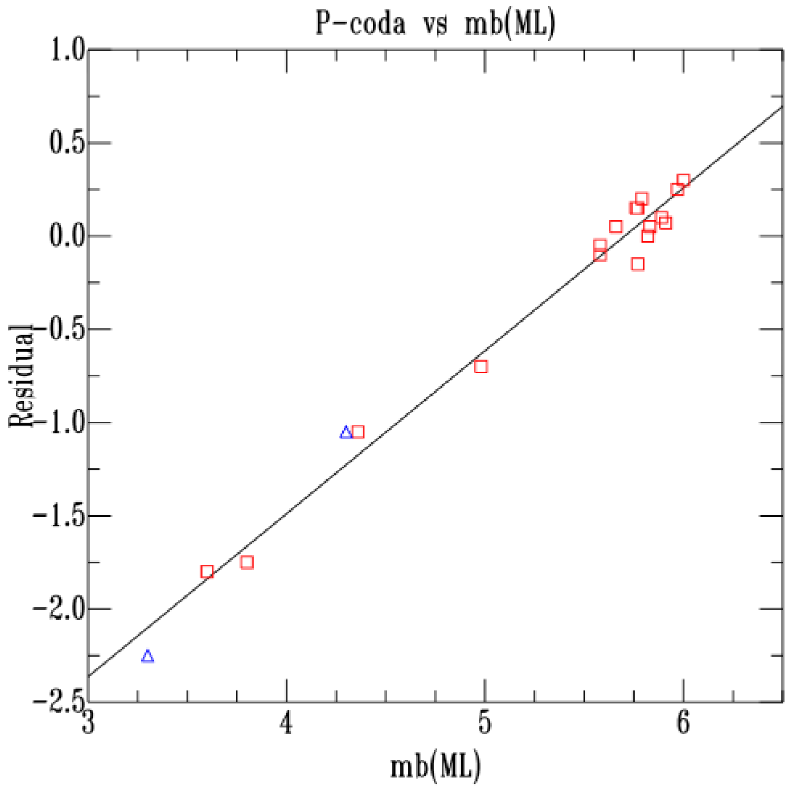

Figure 3.

Paths from NZ to NORSAR are still at regional distance and one might expect the *P*-wave and its coda to be comprised of waves that sample the crust and upper mantle over a range of take-off angles from the source. At teleseismic distances however, we might expect that the averaging nature observed for local and regional coda waves to breakdown. At these distances, first arriving *P*-waves are likely emanating from a limited range of take-off angles near the bottom of the focal sphere. To investigate this, we processed roughly 30 NZ explosions recorded at the U.K. arrays, Eskdalmuir in Scotland (EKA) and Yellowknife in Canada (YKA) located at ~30 and 44 degrees from NZ, respectively.